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Natural convection from a pair of differentially-heated horizontal cylinders aligned side by side in a nanofluid-filled square enclosure

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Abstract

A two-phase model based on the double-diffusive approach is used to perform a numerical study on natural convection from a pair of differentially-heated horizontal cylinders set side by side in a nanofluid-filled adiabatic square enclosure. The study is conducted under the assumption that Brownian diffusion and thermophoresis are the only slip mechanisms by which the solid phase can develop a significant relative velocity with respect to the liquid phase. The system of the governing equations of continuity, momentum and energy for the nanofluid, and continuity for the nanoparticles, is solved by the way of a computational code which incorporates three empirical correlations for the evaluation of the effective thermal conductivity, the effective dynamic viscosity, and the thermophoretic diffusion coefficient, all based on a wide number of literature experimental data. The pressure-velocity coupling is handled through the SIMPLE-C algorithm. Simulations are executed for three different nanofluids, using the diameter and the average volume fraction of the suspended nanoparticles, as well as the cavity width, the inter-cylinder spacing, the average temperature of the nanofluid, and the temperature difference imposed between the cylinders, as controlling parameters, whose effects are thoroughly analyzed and discussed. It is found that the impact of the nanoparticle dispersion into the base liquid increases remarkably with increasing the average temperature, whereas it increases just moderately as the nanoparticle size decreases, as well as the imposed temperature difference and the cavity width increase. Conversely, the distance between the cylinders seems to have marginal effects. Moreover, an optimal particle loading for maximum heat transfer is detected for most configurations investigated.

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Keywords: Nanofluid; Natural convection; Differentially-heated horizontal cylinders; Two-phase modeling; Enhanced heat transfer; Optimal particle loading.

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Nomenclature

c	specific heat at constant pressure, J/(kgK)
D	diameter of the cylinders (m)
D_B	Brownian diffusion coefficient, m^2/s
D_T	thermophoretic diffusion coefficient, m^2/s
d_p	nanoparticle diameter, m
$\vec{g}$	gravity vector, m/s^2
$\boldsymbol{I}$	unit tensor
L	inter-cylinder spacing (m)
$\vec{J}_p$	nanoparticle diffusion mass flux, kg/(m^{2}s)
k	thermal conductivity, W/(mK)
k_B	Boltzmann constant = $1.38066 \cdot 10^{-23}$ JK^{-1}
m	nanoparticle mass fraction
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
Q	heat transfer rate, W
q	heat flux, W/m^2
Ra	Rayleigh number
S_T	thermophoresis parameter
T	temperature, K
t	time, s
U	x-wise velocity component, m/s
$\vec{V}$	velocity vector, m/s
V	y-wise velocity component, m/s
$\vec{V}_T$	thermophoretic velocity vector, m/s
W	width of the enclosure, m
x,y	Cartesian coordinates, m

Greek symbols

δ	dimensionless inter-cylinder spacing
θ	angular coordinate, deg
φ	nanoparticle volume fraction
μ	dynamic viscosity, kg/(ms)
ρ	mass density, kg/m^3
$\boldsymbol{\tau}$	stress tensor, kg/(ms^2)
λ	dimensionless inter-cylinder spacing

Subscripts

av	average
c	cooled wall, at the temperature of the cooled wall

1. Introduction

Buoyancy-induced convection of nanofluids inside adiabatic enclosures containing heated and cooled cylinders has recently gained a lot of interest, due to its relevance to many potential engineering and science applications, such as solar collectors and heat exchangers, just to name a few.

The studies available in the literature on this topic were carried out numerically by Garoosi and colleagues [1,2], and Khalili et al. [3]. However, both studies executed by Garoosi and colleagues [1,2] are based on the single-phase approach, in which nanofluids are treated as pure fluids, assuming that the solid and liquid phases are in local thermal and hydrodynamic equilibrium, thus neglecting the effects of the slip motion that actually occurs between the suspended nanoparticles and the base liquid. Notice that, as thoroughly discussed in a study recently conducted by Corcione et al. [4], these slip effects can be regarded as responsible for the heat transfer degradation detected experimentally in cavities differentially heated at sides. On the other hand, in the two-phase investigation performed by Khalili et al. [3], the thermophoretic velocity of the suspended nanoparticles is calculated by the way of the McNab-Meisen empirical relation [5], whose applicability to water-based nanofluids with suspended metal oxide nanoparticles has never been demonstrated.

Framed in this background, a comprehensive numerical study on natural convection from a pair of differentially-heated horizontal cylinders set side by side in a nanofluid-filled adiabatic square enclosure is performed using a two-phase model based on the double-diffusive approach. It is assumed that Brownian diffusion and thermophoresis are the only slip mechanisms by which the solid phase can develop a significant relative velocity with respect to the liquid phase. The model developed incorporates three empirical correlations for the calculation of the effective thermal conductivity, the effective dynamic viscosity, and the thermophoretic diffusion coefficient, all based on a high number of experimental data available in the literature from diverse sources, and validated using relations from other authors and experimental data different from those employed in generating them. Scope of the present paper is to evaluate the effects of the nature, size and average volume fraction of the suspended nanoparticles, as well as those of the cavity width, the inter-cylinder spacing, the average temperature of the nanofluid, and the temperature difference imposed between the cylinders, on the nanofluid heat transfer performance.